

Validation Data for Microscale Dispersion Modelling

Bernd Leitl
**Meteorological Institute, University
of Hamburg**
Bundesstraße 55
20146 Hamburg, Germany

Proper validation of numerical dispersion models is one of the keys factors for further improvement of model quality and model assessment. For reliable model tests specific validation data must be available that match certain criteria in terms of the quality of the reference data and the completeness of documentation. The following article explains a strategy for compiling wind tunnel data sets for validation purposes.

Motivation

Predicting the dispersion of pollutants at the urban scale is one of the most challenging problems modern environmental research is facing. Most air pollution sources are located within the urban canopy layer and transport phenomena are dominated by a number of complex factors like emission source characteristics, the turbulent structure of the wind as well as the local arrangement of buildings and structures. In order to predict turbulent transport phenomena in built-up areas, a complex obstacle resolving type of dispersion model is required. The results of microscale dispersion modelling are directly used for assessing air quality at the local scale as it is requested by environmental policy. Thus, the quality of microscale modelling has a direct impact on urban planning, on quality of life and human health. In addition, the output of local scale modelling is also used as input for large scale dispersion models. In the hierarchy of environmental models, the local scale modelling

acts as fundament for all following model categories up to the global scale and is therefore affecting the quality of large scale dispersion modelling. From that, it is obvious that quality assurance and model validation play an important role in developing sophisticated micro-scale dispersion models. One of the first guidelines for model validation came from the Commission of the European Communities (CEC's) Model Evaluation Group. According to the "Guidelines for Model Developers" [1], model validation is one of the three basic steps, a complete evaluation of a numerical dispersion model consists of.

From the model developers point of view, a major problem in model validation is having access to qualified reference data. Test cases that can be found in literature usually describe singular situations which cannot be used for a systematic validation of the physics implemented in a microscale dispersion model. Assessing the physical quality of a dispersion model requires analysing the model behaviour when boundary conditions are changed systematically. In addition, most of the data that can be found do not contain a complete documentation of the test in terms of providing all information that is necessary for defining a reference situation unequivocally. Another problem complicating the acquisition of validation data is, that it is often difficult to get a sufficient amount of data in electronic form. It usually requires direct contact to the data provider and most of the data need further time-consuming processing before used for comparison with numerical results.

As a source of reference data results of field measurements as well as laboratory data from boundary layer wind tunnel experiments can be used. However, one

has to keep in mind that both data sources have their specific limitations. Field campaigns in most cases represent unique situations with a rather complex set of boundary conditions. A proper recording of all boundary conditions during field measurements is often impractical because of the limitations in instrumentation. Therefore, in a strict physical sense it is impossible to define exactly what kind of dispersion situation was captured during a field experiment. A second problem related to field data is that of changing boundary conditions like the constantly changing weather cause a large variation in the results even for time averaged measurements. As it could be shown in laboratory experiments and long-term field campaigns, typical half-hour averages of measured flow and dispersion quantities might vary by one order of magnitude [2]. Consequently, the limited representativeness of field data usually limits their usefulness for comparison with the steady-state results of a numerical dispersion model.

A major limitation of wind tunnel data is that wind tunnel results are, strictly speaking, model results which already incorporate simplification and abstraction from the physical reality. For example, most of the wind tunnel data sets are measured in a neutral stratified boundary layer and effects of the Ekman wind spiral are neglected. Nevertheless, wind tunnel data have some major advantages over field data regarding microscale dispersion model validation. First, different levels of complexity of the data sets can be generated, reaching from single obstacle situations and point sources up to detailed physical modelling of complex urban areas. As a second advantage, the boundary conditions in a wind tunnel can be kept constant over a long period of time. Therefore, it is possible to simulate steady-state dispersion like it is modelled by usual microscale dispersion models. The representativeness of wind tunnel measurements normally varies within bounds defined by the accuracy of the laboratory grade instrumentation only. Another important advantage of laboratory data over field measurements is that most of the physical boundary condi-

tions of a test can be controlled, and that all of them can be measured with high accuracy. A complete documentation of a wind tunnel test can provide all information required to clearly identify the physical state of the experiment. This prevents the user of reference data from incorrect comparison and minimizes the risk of misinterpretation of validation data. It is obvious that the benefits of wind tunnel data predominate the restrictions, physical modelling of environmental flows has. If a microscale dispersion model can simulate simplified experiments studied in a boundary layer wind tunnel, it is likely that the same model will predict flow and concentration patterns in complex field situations reliable as well. It is apparent that a model that fails in simple situations will, most likely, not work properly for complex cases. To overcome the main problems related to validation data, the CEDVAL project (Compilation of Experimental Data for VALidation purposes) has been started at the University of Hamburg. Sponsored by the German Federal Environmental Agency, the main goal of the project is to design, set up and maintain a WWW-database of wind tunnel data that meet all essential requirements on validation data with respect to completeness of documentation, quality and accuracy of reference data and easy access.

Basic Demands on Validation Data Sets

Compiling data sets which might be used as reference for numerical models requires consideration of three basic criteria. The first fundamental requirement results from the definition of the state of the flow. Validation data can be called complete only if all the boundary conditions classifying the state of the flow and the conditions of the experiment are measured and documented. For the user of the data, it must be possible to define the physical state of the experiment unequivocally without any further assumptions. The physics of the flow within the urban roughness layer can be classified properly if the following set of quantities is given:

- geometry of the model or test setup
- emission source characteristics
- Reynolds-Number of the flow
- mean wind profile for all 3 components of the wind vector
- mean turbulence intensity profile for all 3 velocity components
- parameter of the logarithmic wind profile (roughness length, displacement height, friction velocity)
- spectral characteristics of the approaching flow
- integral length scale of turbulence
- as well as for non-neutral stratified flow a suitable parameter for the thermal stratification (temperature profile, Richardson-Number, vertical heat flux, Monin-Obuhkov-Length,...)

Although the significance of the boundary conditions varies with the type of test cases, the absence of just one quantity leads to an incomplete data set that can be used only for partial validation.

The second criteria that needs to be met by reference data results from the input values required to run a certain type of numerical model. If direct comparison of reference data with results of a numerical simulation is intended, all input values and boundary conditions of the numerical model should be derived from the reference data set only. Considering the different kinds of numerical microscale dispersion models currently available, it can be realized that all the input quantities can be obtained from the boundary conditions required for classifying the flow status. Widespread gradient transport models share a common set of quantities that consists mainly of time averaged mean values of the main wind speed or derived parameters from a mean wind profile, the standard deviation of wind direction, parameters for classifying the thermal stratification and the emission source information. So-called prognostic models are usually based on statistical simulation of turbulence (modified k-model, Reynolds-stress-model etc.). In addition to the input data of common analytical models more complex prognostic simulations can easily process dis-

crete fields of input quantities, for example pressure and wind flow distribution at the inflow boundary of the computational domain. The atmospheric turbulence is usually characterized by the kinetic energy of turbulence k , the dissipation ratio ϵ , the integral length scales of L_{ij} and/or the viscosity ratio ν_t/ν . Again the emission source information is required as input in case of dispersion modelling. Even though the input values of prognostic models are more complex, they all can be developed from a data set that is complete in the sense of providing all essential information on boundary conditions. Unfortunately, some of the required input values cannot be measured directly and therefore need to be derived from combinations of measured quantities. Thus, maintaining a high accuracy and reliability of all measurements is essential for compiling data with reference quality. For completeness, the requirements resulting from the next generation of microscale dispersion models needs to be mentioned. It is likely that in the future Microscale dispersion models will be based on a more or less direct numerical simulation of highly turbulent atmospheric flows. Subsequently, this type of model will require time series of all measured boundary conditions for input. Compiling validation data for evaluating numerical dispersion models should therefore consider time series of measured quantities at least as an option.

The third demand on validation data is characterized by a complete documentation of the reliability of the reference data and the error bands of all measured quantities. Measured quantities can only be used for validation purposes if the uncertainty of the data is documented and proofed to be small enough. Documenting the repeatability of all measurements can help assessing the quality of a comparison of numerical results with validation data more realistically. Furthermore, it provides the confidence a user needs to accept laboratory data as a quality standard. In addition, validation data sets should provide sufficient information on how the data were acquired, what the basic results of the test were and how the results compare with similar tests that

might be found in literature. Such information essentially would help for better understanding the measurements and using the reference data more effectively. Besides, it helps to avoid misinterpretation or overrating of the validation data.

A Structured Set of Test Cases

Validation does not only occur at the final state of model development. From the very beginning up to the final model check the model developer needs test data for assessing the quality of all the implemented algorithms of a complex microscale dispersion model. In an early state of model development partial validation takes place for instance in order to assess the quality of the turbulence model that will be implemented. By that time modellers usually look for rather simple test cases that can be set up for test runs easily. In terms of density of the data, an early state test case should provide as complete as possible measurements of all essential quantities. Ideally, such a test case would be characterized by a density of measurement points at least as dense as the maximum geometrical resolution of the numerical model. Providing a high density of measured data reduces the risk of misinterpretation of effects of geometrical distortion or limited geometrical resolution of the numerical model when comparing model results with reference data. In addition, large scale flow and dispersion patterns will be resolved completely within a narrow grid of measured reference data and a very first model comparison can be carried out quickly by comparing the size and location of large scale flow and dispersion structures.

A second step of model development is reached when all the parameterisations are fixed. By that time, model validation usually means testing the model against more complex reference situations with systematically changing boundary conditions. A systematic variation of boundary conditions or methodical changes in the geometry of the test situation allows for testing the correct "physical behaviour" of model results when parameters are changed in defined steps. Considering that the model already has been checked

for sufficient representation of all significant flow and dispersion structures, like flow separation and re-attachment zones or re-circulation areas, the density of the data (= number of measurement points) might be less than in the first case. Instead, the data acquisition should now focus on providing a number of test situations with several sets of experimental results for systematically changing configurations.

A third category of validation data is needed for final evaluation of a numerical dispersion model before it is used for practical applications. In order to assess both the physics of the model and the handling of the code in realistic situations, results from complex and detailed physical modelling of field sites could be used. Based on a careful comparison of field measurements with corresponding wind tunnel data from a detailed physical model, the quality of the wind tunnel data can be rated with respect to field measurements and a characteristic representativeness (~ error band) can be assigned to field data. Quantifying the reliability of field data by comparison with results from detailed physical modelling supplies, information on how "accurate" the numerical model must really meet field data. For this category of reference data the total number of measurement points must be reduced at the expense of detailed modelling of very complex field sites. Nevertheless, linking field site data with results from detailed wind tunnel modelling for validation purposes reduces the effect of the limitations both techniques have in terms of representing the "physical reality".

Realization of an Internet-Database

Within the scope of the CEDVAL project, a database has been setup at the University of Hamburg in order to provide reference data that meet all the requirements mentioned above. A number of new high resolution wind tunnel data sets has been generated in the BLASIUS boundary layer wind tunnel [3] of the Meteorological Institute.

For flow measurements a DANTEC[®] 2D Laser-Doppler-Anemometer is used and concentration measurements are carried out by means of a high resolution FastFID (Cambustion Ltd.). For quality assurance all measurement devices as

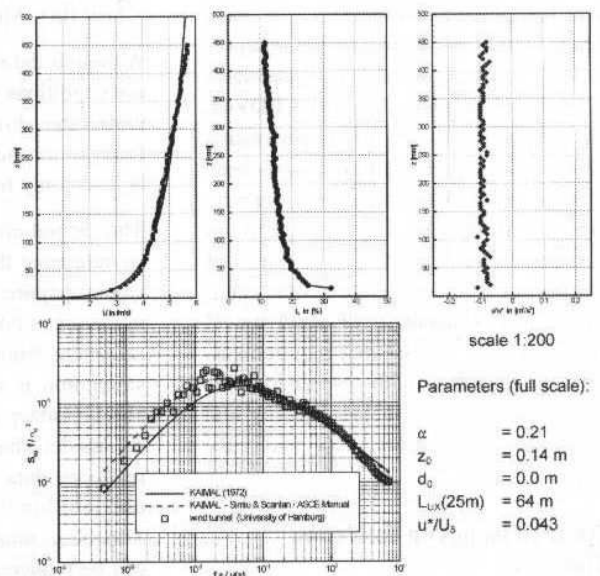


Figure 1: Boundary conditions / approaching flow of a typical wind tunnel boundary layer (model scale 1:200).

well as the electronic tracer mass flow controllers used for emission modelling are checked against independent standards before each experiment. To guarantee a high accuracy and resolution in probe positioning, the wind tunnel was equipped with a computer controlled 3D probe positioning system which provides sub-millimetre accuracy on all three axes. Data acquisition and probe traversing system are controlled by a PC equipped with advanced multi-functional data acquisition hardware. An extensive,

Windows-based software package has been developed for high accuracy probe calibration, automated data acquisition, validation of measured quantities and online data reduction. Due to the high efficiency of the wind tunnel testing even complex measurement tasks like acquiring reference data for the validation of microscale dispersion measurements can be realized in an acceptable amount of time.

clickable map. The open structure of the data set makes it easy to add additional data sets as they may be provided by other laboratories. The only requirement that needs to be met by data for publication is that all essential information a complete data set consists of can be given by the data provider. It is also possible to extend the group structure by additional categories of data sets, for instance to publish special data sets for specific

Example Data Set - Flow and Dispersion Around a rectangular Building

As an example, some results of flow and dispersion measurements around a single rectangular building are presented in Figure 1 - 3. Figure 1 documents the flow approaching the model building. As it can be seen, a wind profile with a power law exponent of $\alpha = 0.21$ was established. The turbulence intensities and the spectral characteristics of the approaching flow agree well with data given by field experiments. The 1:200 model scale of the modelled boundary layer flow was realized by means of a customized spire - floor roughness - configuration. Figure 2 shows a part of the 2D velocity vectors measured in several horizontal and vertical measurement planes as well as streamlines calculated from measured data. Because of the dense grid of measurement points, zones of flow separation, re-attachment and flow re-circulation can clearly be detected. For this data set mean velocities, turbulence intensities and shear stresses were measured at 1246 locations. Due to the extensive efforts in quality assurance a typical repeatability of better than 98% can be stated for all flow measurements. Figure 3 represents a small fraction of the

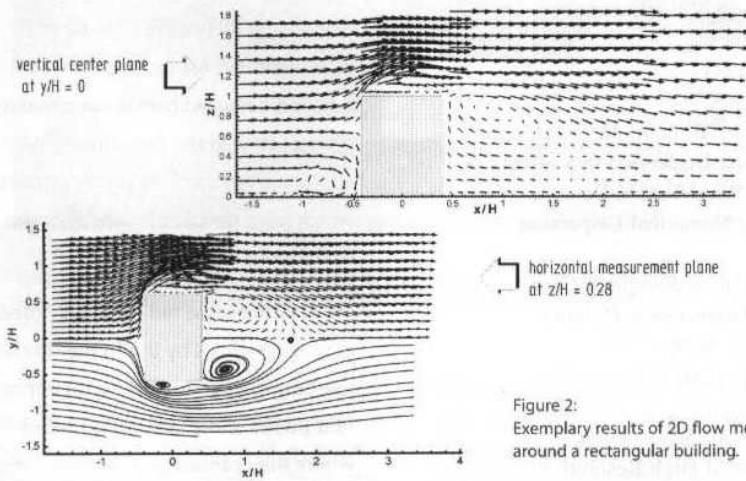


Figure 2: Exemplary results of 2D flow measurements around a rectangular building.

In order to provide access to all data sets compiled so far, a website for electronic data publishing has been setup. The CEDVAL website [4] has been kept rather simple for the sake of being user friendly and easy to use. In addition to the data sets users will find some general information on how the data have been compiled as well as a list of additional data providers. One of the fundamental design concepts of CEDVAL was to publish all reference data sets exactly in the same way. Thus, a complete data set always consists of a set of ASCII- and image files that follow the same strict naming convention. So it should be easy to find the required information within different data sets once the user got used to the naming convention. The files, a data set consists of, can be read online or downloaded as a whole in order to work with the reference data offline. The different test data sets are grouped according to their complexity and browsing in the data set is made easy by means of a

dispersion models (accidental releases, odour dispersion models etc.).

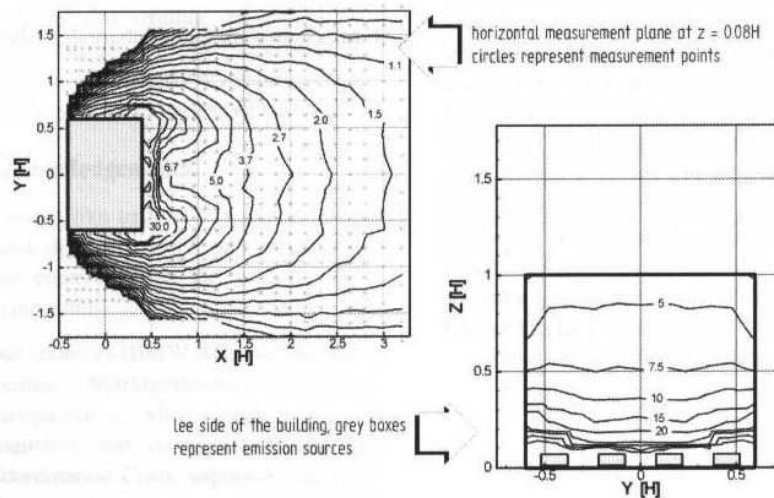


Figure 3: Exemplary results of high resolution immission measurements in the vicinity of a rectangular building with four emission sources attached close to the ground on the leeward side of the building.

results of emission modelling. Attaching 4 area sources close to the ground on the leeward side of the model building, emissions from an underground parking garage were simulated. Subsequently, the dispersion pattern around the model building than was measured at 1228 measurement points. Precisely controlling the emissions and frequently checking the calibration of the FastFID, a repeatability of better than 96% could be reached during immission measurements. Besides the given example, several other configurations have been measured and documented so far and a number of more complex situations will be added until December 1999. Additional data sets which were generated for testing turbulence closure schemes within the BMBF Troposphere Research Program and EUROTRAC-SATURN can also be found in CEDVAL.

Conclusions

Compiling reference data sets for the validation of numerical dispersion models requires more than just publishing results of regular field site measurements or wind tunnel tests. If data are supposed to be useful as a reference for assessing the quality of microscale dispersion models, they must follow a significantly higher standard of documentation, accuracy and reliability. The list of demands on validation data which has been derived based on fluid mechanical criteria as well as based on requirements of dispersion models represents a minimum in terms of standards that need to be met by reference data. The CEDVAL database is a first approach in order to publish high quality reference data systematically. Everybody is invited to provide reference data that can be included in the CEDVAL web archive in order to make this site a useful tool for model development and testing in the future.

Acknowledgment

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